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Wetland loss impact on long term flood risks in a closed watershed

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ABSTRACT

Flood control is one of the most important ecosystem services provided by wetlands. Large-scale loss of wetlands, combined with more intensive precipitation under changing climate, increases flood risks, to which closed watersheds are particularly susceptible. In the Devils Lake (North Dakota, USA) watershed, a prolonged wet condition since early 1990s has caused a nearly 10 m rise in water level, resulting in over $1 billion losses. While studies have shown the changing climate is the major driver of this flooding, it is still unclear how much contribution could be due to the historical conversion of wetlands in the upper basin. We developed a Soil and Water Assessment Tool (SWAT) model for the Devils Lake watershed and simulated various scenarios representing present and possible past and future wetland area. We estimated the changes in flood risks under the historical and CMIP-5 future climates with these wetland scenarios. We found that while currently wetland restoration does not significantly change flood risks, under the modified climate it presents a good complementary measure reducing the negative impacts of current flood management strategies.

1. Introduction

Approximately 6% of the Earth's surface is covered by wetlands, which, however, is believed to be only half of the original area prior to anthropogenic modification of the planet (Maltby and Acreman, 2011). Wetlands provide numerous ecosystem services, including biodiversity maintenance, carbon sequestration, nutrient cycle regulation and many others; these services have been extensively studied (for review see Maltby and Acreman, 2011). One of the important ecosystem services of wetlands is flood control. In this respect, the wetlands are long known to "act like a sponge" (Turner, 1784, p. 30), reducing the peak water surge. Bullock and Acreman (2003) provided a thorough review of the researches detailing the role of wetlands in the hydrological cycle.

Despite these early studies, the ecosystem services provided by wetlands had not been widely recognized and accepted until recently, leading to a widespread conversion of wetland ecosystems worldwide. It is estimated that 54–57% and possibly as much as 87% of the global wetlands were lost since the beginning of the 18th century (Davidson, 2014). In the 20th century, the conversion of wetlands to other land uses, primarily agriculture, has accelerated. Globally, the highest rate of inland wetlands loss was observed in Asia (with a loss rate of 1.885%/yr) and the lowest (0.347%/yr) in North America (Davidson, 2014). In the contiguous USA, 53% of original wetlands were lost between 1780 and 1980 (Dahl, 1990). Even North Dakota, the third least populated state with a population density of 10.5 people per km^2, lost 49% (approximately 10,000 km^2) of its original wetlands. In addition to the acreage loss of wetlands, the ecosystem services provided by the wetlands were also altered, including impaired water quality, increased flooding risks, impacted biodiversity, and reduced atmospheric carbon sequestration (Zedler and Kercher, 2005).

In a changing climate, the role of wetlands in flood control becomes even more important. Milly et al. (2002) reported that the risks of "great floods" (the floods with discharges exceeding 100-year levels) have substantially increased throughout the past century. This trend is projected to continue in the future, with the flood rate increasing two to eight times as compared to historical observations (Milly et al., 2002). Globally, Hirabayashi et al. (2013) found that under climate change flood frequency increases in 42% and decreases in 18% of the land area.

Despite mounting evidence on the role of climate change in modification of flood risks, there are little indications that people connect floods with climate change, even when they are recent flood victims and/or generally agree that flood frequency is increasing nowadays (Whitmarsh, 2008). These observations elevate importance of case studies in the regions suffering flood consequences due to changed climate. Closed lake watershed presents a good object for such case

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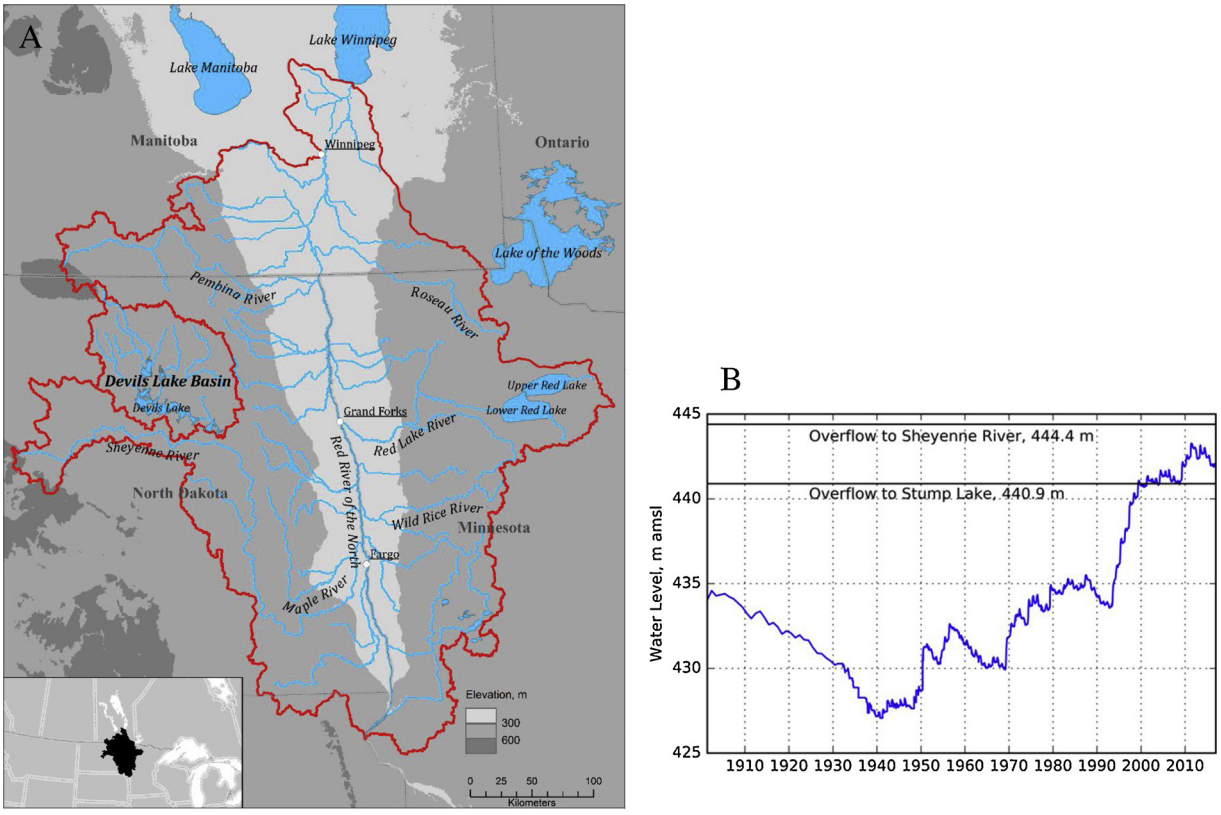

Fig. 1. A: Devils Lake and Red River of the North basin boundaries (red lines); B: The change of Devils Lake water level. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

studies due to their vulnerability to amplified effects of regional climate change.

Closed (also called endorheic or terminal) lakes are confined within land with no outflow (De Martonne, 1927). Because of that, water balance of a closed lake only depends on water inflow, precipitation, and evaporation (Bengtsson and Malm, 1997; Williams, 1996), making the lake a good indicator of climate and land use changes in the entire watershed. Kharel and Kirilenko (2015) provided an overview of observed changes in closed lakes worldwide. An example of such lakes is Devils Lake in North Dakota, USA. Devils Lake (DL), located in the Northern Great Plains of the U.S., is a saline terminal lake, and together with the adjoined Stump Lake, has a drainage area of approximately 9850 km^2 (Fig. 1A). Since its formation at the end of Wisconsin glacial period roughly 10,000 years ago, the lake has experienced multiple water level fluctuations between dominantly dry (6500 years ago) and at least two overspills beyond the watershed boundary within the past 4000 years (Wiche and Vecchia, 1996). The latest episode of long term retreat of DL water level was traced from 1867 when it was first measured by the U.S. Geological Survey (USGS) at 438 m amsl and had continued until the 1940s when it decreased to 427 m amsl. The subsequent period of long-term water level rise accelerated rapidly in the 1990s–2000s; since 2000, DL water level had increased by 8.5 m with the highest level of 443.27 m amsl recorded in June of 2011 (Fig. 1B). Beginning in 1999, Devils Lake begun to overflow to the nearby Stump Lake, which it completely merged in 2007. The merged lakes will be referred to as Devils Lake hereafter.

The recent rapid rise of Devils Lake water flooded over 650 km^2 of prime farmland, inundated parks and historical landmarks, and eroded coastal infrastructure including the roads, railroad, and dams. The rising waters impacted multiple communities, including half of the Native American Spirit Lake Tribe population (Spirit Lake Tribe and FEMA, 2010). Despite very low population density in the region (3.4 person/km^2), the total impact on business activity was estimated at $200 M (Noone, 2012). These flooding costs, however, are dwarfed by the $1B expenditures on flood mitigation (Noone, 2012). The overall impact of DL flooding influenced the economy and policy well beyond the region (Aakre et al., 2013, 2013; Ma et al., 2011).

If the observed flooding continues and the water level rises up to 444.4 m amsl (1.1 m above its record high), Devils Lake would overspill beyond its watershed to the Sheyenne River, one of the major tributaries of the Red River of the North, ultimately flowing into the Hudson Bay. The uncontrolled overspill would result in a rapid release of 40% of the accumulated lake water at a rate of 340–453 m^3/s (Larson, 2012), potentially leading to a catastrophic flooding of the downstream communities in the USA and Canada. To reduce flooding risks, a "three-pronged approach" was introduced by the DL Basin Joint Water Resource Board as a mitigation strategy, which includes: (1) operating the outlets for controlled water draining to Sheyenne River (Fig. 2), (2) building flood managing infrastructure, and (3) land restoration in the upper watershed (DLB Joint Water Resource Board, 2013). The latter measure includes restoration of 110 km^2 of wetland habitats. Furthermore, to prevent devastating downstream flooding, a Tolna Coulee Control Structure was constructed in 2012, limiting the potential DL overspill water flow at a maximum rate of 85 m^3/s.

Previous studies have been focused on the role of climate change (Kharel and Kirilenko, 2015, 2018; Vecchia, 2008) and land use conversion from rangeland to crop production (Kharel et al., 2016). The changes of wetlands over the time in the region have been studied (Doeing and Forman, 2001; Gehringer and Hove, 1998; Ludden et al., 1983). However, how these changes could have impacted the Devils Lake flooding has not been thoroughly researched, which leads to the first objective of this study. The second objective is to estimate possible role of wetland restoration as an alternative measure reducing the negative impacts of current flood management strategies. The rest of the paper is structured as follows. First, the data and approaches to model the hydrology of the DL watershed, scenarios of wetland area

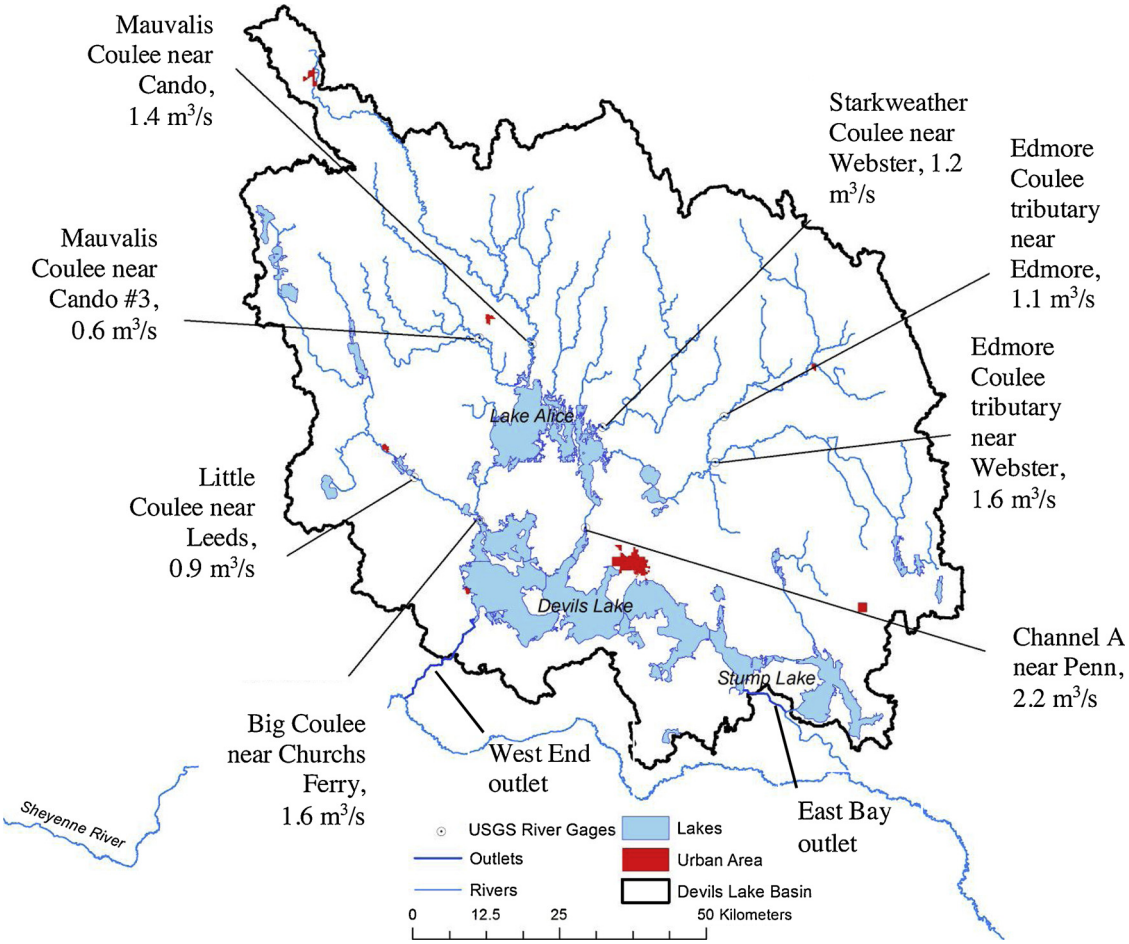

Fig. 2. Location of the DL outlets and USGS stream gauges showing the mean annual discharge.

distribution, and downscaled climate scenarios are introduced. Second, the results of flooding risks in current and future climates are presented for the wetlands scenarios introduced in the previous part. Finally, broader implications of these results are discussed.

2. Methods and data

2.1. Environment and climate

The Devils Lake watershed is generally flat with elevation varying from 423 to 675 m amsl (Fig. 3A). Being a part of the greater Prairie Pothole Region, the area is characterized by numerous small depressions (Euliss et al., 1999). The interconnecting potholes may be dry or contain water, depending on weather, hence playing an important role in retaining surface runoff. The soils in the region are mainly of hydrologic group B and C of loam and clay types that have moderate to low water infiltration rates (Fig. 3B), increasing surface runoff and contributing to high flood risks in the basin. The eastern part of the basin is occupied by the loamy, poorly drained Hamerly soil type (U.S. Department of Agriculture, 2009). The satellite imagery (Fry et al., 2011) shows that the dominant land cover type in the DL basin (Fig. 3C) is cropland (60.0% of the area), followed by grassland (14.7%). Urban and developed areas occupy 4.1% of the watershed. One fifth of the watershed is occupied by wetlands and open water (10.7% and 9.9% respectively).

The regional climate is temperate/humid continental with warm summers and dry winters; a majority of precipitation is observed in June and July while winters are dry (Hoerling et al., 2010). Climatic normal (1981–2010) precipitation is 468 mm and the annual temperature is 4.2 °C. The mean annual precipitation over the watershed is nearly balanced by evapotranspiration with a cold season water surplus and warm season deficit (Hoerling et al., 2010). This results in a strong seasonality in surface runoff, leading to a typical rapid rise in DL water level in March–May followed by a slow decline in other seasons. The long-term change in precipitation over the DL area is caused by a superposition of a continental-scale shift towards wetter conditions in the 1970s–1990s and a regional oscillation between a dryer pattern in the 1970s–1980s and wetter conditions starting in the 1990s (Hoerling et al., 2010). The combination of these two factors accelerated regional shifting towards wetter conditions in the 1990s. Since the lake only occupies roughly 6% of the watershed area, small shifts in precipitation pattern over the watershed, especially during the winter and spring period, result in large changes in the lake's water level.

2.2. Hydrological model

The hydrology of the Devils Lake basin was simulated using the Soil and Water Assessment Tool (SWAT 2012) (Neitsch et al., 2011) with a daily time step. The following data about the watershed are required by SWAT: digital elevation model (DEM), river network, land cover, soil, and weather. We used a 1 arc-second (approximately 30 m) DEM from the National Elevation Dataset (U.S. Geological Survey, 2009) because previous studies indicated that higher DEM resolution has no significant improvement of streamflow and runoff simulation (Lin et al., 2010; Tan et al., 2015). For river network, the National Hydrography Dataset (U.S. Geological Survey, 2013) was used. The land cover map was extracted from the NLCD National Land Cover Dataset (Fry et al., 2011; Homer

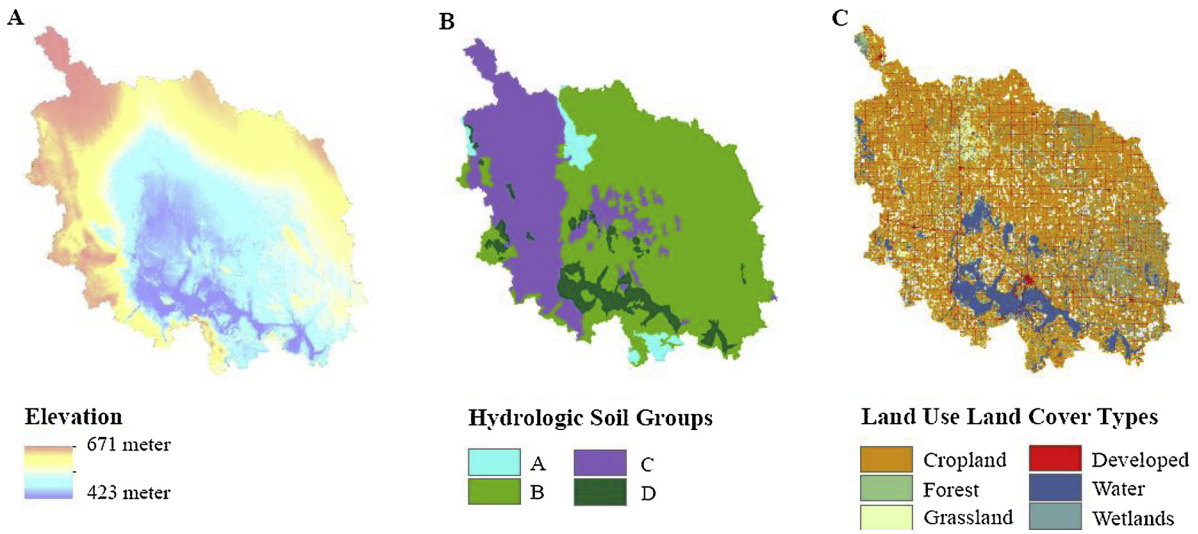

Fig. 3. Topography (A), hydrologic soil groups (B), and the land use land cover (C) maps of the Devils Lake basin. Source: USGS (see Appendix for details).

et al., 2007) and aggregated into Anderson Level 1 classes (Anderson, 1976). Soil data was obtained from STATSGO database (Natural Resources Conservation Service, n.d.).

SWAT model was calibrated and validated using the 1989–2010 observational data of the daily streamflow recorded at seven different USGS stations and Devils Lake water levels (Appendix) with assistance of SWAT-CUP software (Abbaspour, 2007). For the reservoir simulation, the 2001–2010 data were used for calibration with 1999–2000 as warm-up and 1991–2000 data were used for validation with 1989–1990 as warm-up. The operation of two DL water outlets (Fig. 2) was ignored in calibration and validation because the West End outlet, though was completed as early as 2005, was mostly non-operational until 2011, resulting in a negligible volume of water pumped from the lake, and the East Bay outlet was not completed until 2012. For future climate simulations, however, we assumed that both outlets pump an average of 11.2 m^3/s during the months of active water pumping (May–October). This value was estimated based on the 2011–2014 outlet operation schedule (North Dakota State Water Commission, 2017).

The streamflow calibration and validation indicated a satisfactory model performance with the Nash-Sutcliffe efficiency (NSE) values ranging from 0.51 to 0.86 between different USGS gauges (see Appendix for more details). The performance of model calibration against the observed elevation of Devils Lake was evaluated using the standardized root-mean-square error (RSR) and the percent bias (PBIAS) following recommendations of Moriasi et al. (2007). The RSR is computed as a ratio of RSME to the standard deviation of the observed data and ranges from 0 for a perfect fit between model predictions and observations to infinity. Smaller RSR values indicate a small RMSE relative to the natural variability of the lake levels. The RSR values are 0.31 for calibration and 0.22 for validation (Fig. 4, Table 1); both values are smaller than 0.5, indicating a very good model fit (Moriasi et al., 2007). PBIAS measures a systematic deviation of the simulated values from the observations; PBIAS = 1.4% for calibration and 11% for validation, both indicating a good model fit (Moriasi et al., 2007). Finally, RMSE = 0.14 m for the calibration and 0.59 m for validation period. The relatively greater error during the validation period is mainly due to a rapid increase in DL water level during the validation period, followed by a more gradual increase and stabilization during the calibration period. We hypothesize that the primary reasons for the systematic overestimation of the lake level during the period of its fast increase could be (1) a lack of accounting for micro-depressions in the model and (2) relatively simple wetland model used. Nevertheless, model fit remained evidently good during the entire period of simulation. See details on the model calibration and validation in Appendix.

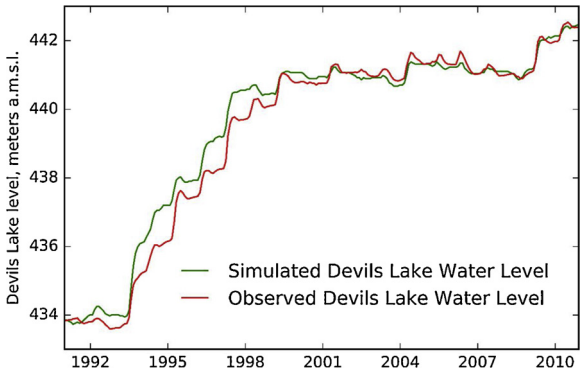

Fig. 4. Comparison of observed and simulated Devils Lake water levels.

Table 1
Model calibration (2001–2010) and validation (1991–2000).

Period	Mean observed elevation, m	Mean simulated elevation, m	RMSE, m	RSR	Pbias, %
1991–2000	437.3	437.8	0.59	0.22	−11.0
2001–2010	441.3	441.2	0.14	0.31	1.4

2.3. Scenarios of wetland area change

Currently, wetlands occupy approximately 10.7% of the DL basin area, based on the NLCD 2006 remote sensing data. Tiner (1984) reported a 60% loss of the historical wetlands in North Dakota. Estimates for the wetland loss in Devils Lake watershed are few and vary between 31% (Doeing and Forman, 2001) and 47% (Sapa, 1997). A continuing wetland reduction trend in Dakota Prairie Pothole region is reported as 0.3%/yr. Using these estimates, we constructed the following wetland area change scenarios:

(1) no wetlands, representing an extreme case where all the wetlands are drained;
(2) wetlands occupy 5% of the watershed area, representing an approximately 50% reduction from the current wetland coverage, for example, under increased pressure to convert additional area for agriculture;

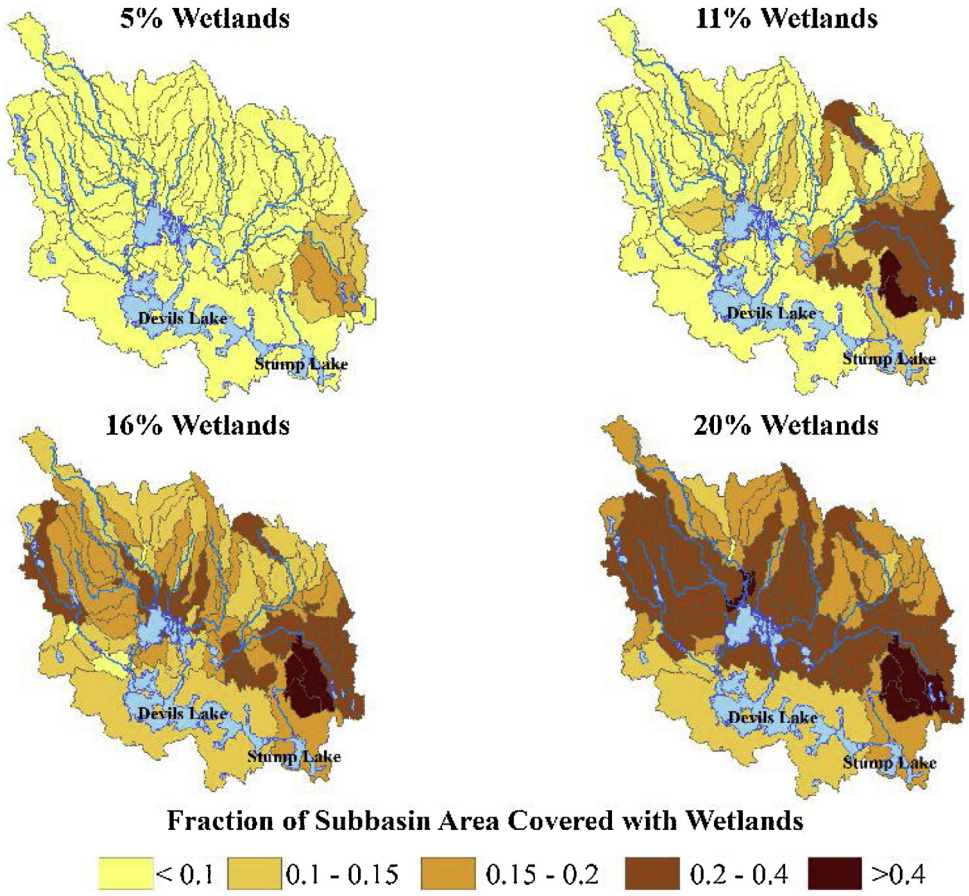

Fig. 5. Distribution of wetlands in the watershed in hypothetical scenarios with wetlands occupying 5%, 11% (current), 16%, and 20% of the watershed.

(3) wetlands occupy 10.7% of the watershed area, representing the current wetland area;
(4) wetlands occupy 16% of the watershed area, representing a moderate estimate of the historical wetland area (~50% increase from the current area); and
(5) wetlands occupy 20% of the watershed area, representing a high estimate of the original wetland coverage and/or enhanced wetland conservational efforts.

A compound topographic index CTI (Beven and Kirkby, 1979) was used to estimate the locations in the watershed where a wetland could most likely be restored or drained. Studies have shown that CTI is a good determinant of surface soil water content (Moore et al., 1991) and wetlands locations (Cress et al., 2009; Murphy et al., 2007). For each DEM pixel, $CTI = \ln \frac{\alpha}{tan\beta}$, where α is the contributing area of the upland cells and β is the cell slope in radians. For scenario (2), the land type of the "driest" wetland cells (those with the smallest CTI) were replaced with croplands. Similarly, for scenarios (4) and (5), the land type of the "wettest" cropland cells (those with the highest CTI) were replaced with the wetlands (Fig. 5). Finally, wetland storage and fraction of wetlands were estimated using a statistical model by Gleason et al. (2008), which used the observations from Prairie Pothole Region wetlands to estimate a wetland's contributing area A_c (ha) and volume V (ha m) as a function of its area A (ha): $V = 0.25A^{1.4742}$; $A_c = 2.24A^{0.4647}$.

2.4. Climate scenarios

To account for model uncertainty (Arnell, 2004), future climate scenarios were generated using the projections of 17 Global Circulation Models (GCMs) included in the Coupled Model Intercomparison Project Phase 5 (CMIP5: https://cmip.llnl.gov/cmip5) of the World Climate Research Programme (WCRP): BCC-CSM (v. 1.1 and 1.1 m), CSIRO-Mk3.6.0, FIO-ESM, GFDL (CM3, ESM2G, and ESM2M), GISS (E2-H and E2-R), HadGEM2-ES, IPSL (CM5A-LR and CM5A-MR), MIROC (ESM, ESM-CHEM, and MIROC5), MRI-CGCM3, and NorESM1-M. This is an accepted way of dealing with GCM biases (Faramarzi et al., 2013). Future change in human activities is simulated using four Representative Concentration Pathways (RCPs): RCP2.6, RCP4.5, RCP6, and RCP8.5 (Moss et al., 2010), where the numeric part of the name indicates the additional radiative forcing in 2100 relative to the base climate (W/m^2).

To account for bias in the GCM climate ensemble, the projections were statistically downscaled with Marksim weather generator (http://www.ccafs-climate.org/pattern_scaling/) using the 1991–2010 weather as the base climate. Furthermore, to account for the climate variability, the weather samples were grouped into 1-year periods and then reshuffled 20 times. This resulted in a total of 1360 30-year weather samples generated for each wetland scenario to characterize the "future" climate; or in other words, future climate simulations included 1360 independent model runs, each lasting 30 years. From these future simulations, we then estimated the DL overspill risks from the distribution of the maximum lake levels achieved in each simulation. On average, projected precipitation over the regions increases by 3.6–5.1% while the temperature increases by 0.5–3.0 °C over the base period with the range accounting for model and scenario variability. We used a similar methodology to construct synthetic multiple 20-year long "current climate" weather series using the 1991–2010 weather data without the GCM projections. In SWAT simulations for the future, the outlet operational schedule was assumed from the 2011–2015 operational data.

Table 2
Mean Devils Lake area and elevation under three wetland scenarios using the current climate simulations (see Section 2.3). The "Running outlet" scenario applies the 2011–2015 outlet operational schedule throughout the entire simulation period. The observed maximum elevation was 443.3 m with the area of 849 km^2 according to the Devils Lake and Stump Lake elevation-area-volume table[a].

Scenario	Running Outlet		No Outlet	
	Area, km^2	Elevation, m	Area, km^2	Elevation, m
11% wetlands	638	441.7	693	442.2
16% wetlands	595	441.4	608	441.5
20% wetlands	548	440.9	552	440.9

[a] www://nd.water.usgs.gov/devilslake/pdf/elevation-area-volume.pdf.

3. Results

SWAT simulations under the historical 1991–2010 climate and with different wetland/outlet operation scenarios (see Section 2.3) show that DL water level is sensitive to the amount of wetlands in the basin (Table 2; Fig. 6). Generally, a 5% increase in the fraction of wetlands in the basin leads to an approximate 0.5 m decrease in DL water level over the 20 years of simulation. The main effect of wetlands is reduction of the peak stream flow, which contributes to the increase of DL water level. For example, wetland scenario 4 (additional 5% of watershed is restored to wetlands) reduces the peak water discharge into the lake from its main tributary (Big Coulee) by 1.5 m^3/s in April and by 3.5 m^3/s in May (Fig. 7). In agreement with the earlier discussion of Devils Lake water balance seasonality, we found that during the spring months (March–May) the difference in water discharge into DL under the wetland restoration and current scenarios is correlated with monthly streamflow ($r = 0.37$; $p < 0.01$), however there is no significant correlation during other seasons.

At the 444.4 m amsl water level, DL would overspill into the Sheyenne River. To estimate the overspill risks, we run multiple 30-year long watershed simulations under varying climate conditions. The overspill risk was defined as the number of simulations in which DL exceeded the overspill level divided by the total number of model runs. Similar to the previous discussion, we found that the area of wetlands strongly affects the overspill risks (Table 3, top half of the Current climate column). In the current climate, wetland restoration reduces the risk of water overspill. For example, an increase in wetland area from the current 10.7% of the watershed to the moderate estimate of the historical area (16% of the watershed area) reduces the overspill risk from 5% to 1%. In contrast, reduction of the wetland area leads to a sharp increase of the overspill probability. For example, an approximately 50% reduction in wetland area from current 10.7% to 6% is projected to elevate the overspill risks from 5% to 9%. While we did not find any evidence that wetland restoration could be a viable *alternative* to functioning outlets, which are found to be much more effective in containing overspill risk (e.g., comparing the top and bottom parts of the Current climate column of Table 3), wetland restoration is nonetheless an important *supplement* to the current main strategy of water management.

The change of climate to wetter and warmer conditions elevates DL overspill risks from 5% to 17% under RCP6.0 scenario and up to 32% under RCP8.5 (right part of Table 3). On average, under the climate change scenarios, the role of wetlands in flood risk reduction is even greater with complete wetland restoration (scenario 5) reducing the risks from 26% to 11% and complete conversion of wetlands to agriculture (scenario 1) elevating the risks of overspill to 44%. Similar to the current climate model run, wetland restoration cannot replace outlet operation; even the total restoration of historical wetlands carries a 42% risk of downstream flooding in absence of water pumping.

4. Discussion

Our results further confirmed the conclusions of the earlier studies that the major driver of DL flooding is regional climate variability (Bluemle et al., 1999; Kharel and Kirilenko, 2015; Vecchia, 2011). For example, in the absence of outlet operation and under the current climate the risk of DL overspill in the following 20 years is 81% and an increase of the wetland area to the historical estimates (scenarios 4 and 5) is only able to reduce this risk to 16–40% (Table 3). We however also found a significant role of large scale conversion of wetlands to agriculture has amplified the negative consequences of the climate shift. Consistent with other studies (e.g., Bullock and Acreman, 2003),

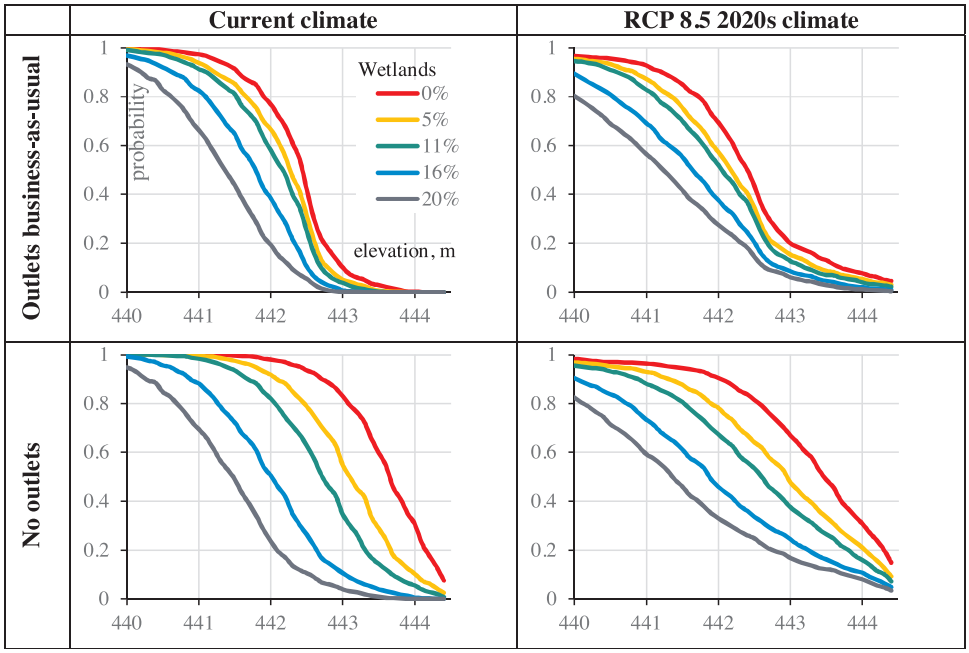

Fig. 6. Annual exceedance probability curves for current (representative of 1991–2010 climate) and future climate simulations (representative of RCP 8.5 2011–2040 climate), with and without running water outlets. Current distribution of wetlands corresponds to the 11% curve.

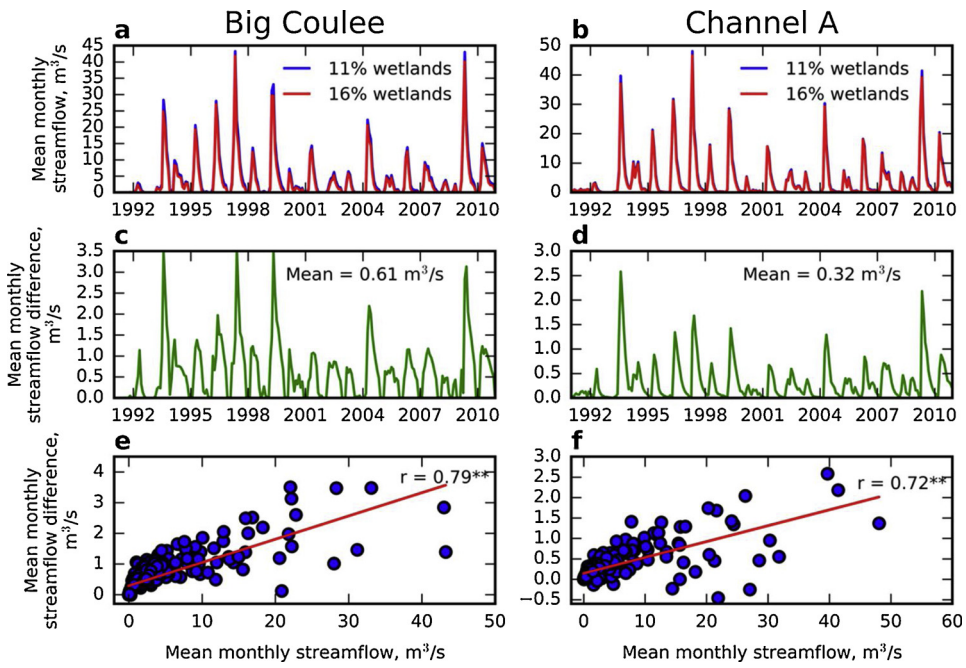

Fig. 7. Comparison of simulated streamflow on the Big Coulee (a, c, and e) and Channel A (b, d, and f) for 11% and 16% wetland scenarios using the current climate scenario (representative of 1991–2010); (a) and (b) - monthly streamflow; (c) and (d) - streamflow difference; (e) and (f) - streamflow difference vs. monthly streamflow.

Table 3
Probability of natural overspill of Devils Lake at 444.4 m amsl under the 1991–2010 climate and future climate projections, for five wetland area scenarios. The top part of the table represents the lake's water level with the current (2011–2015) schedule of outlet operation. The bottom part shows the overspill risks without functional outlets.

	Scenario	Current climate	Future climate				
			RCP2.6	RCP4.5	RCP6.0	RCP8.5	Mean
Running Outlet	(1) No wetlands	19%	44%	44%	36%	52%	44%
	(2) 5% wetlands	9%	34%	36%	24%	36%	32%
	(3) 11% wetlands/current	5%	29%	26%	17%	32%	26%
	(4) 16% wetlands	1%	18%	16%	11%	21%	16%
	(5) 20% wetlands	0%	11%	11%	7%	16%	11%
No Outlet	(1) No wetlands	100%	89%	88%	89%	93%	90%
	(2) 5% wetlands	97%	80%	81%	79%	82%	80%
	(3) Current (11% wetlands)	81%	72%	74%	71%	74%	73%
	(4) 16% wetlands	40%	54%	59%	51%	56%	55%
	(5) 20% wetlands	16%	41%	46%	40%	41%	42%
	Precipitation (mm/day)	1.42	1.48	1.48	1.47	1.49	1.48
	Average daily Temperature (°C)	3.60	5.17	5.19	4.98	5.29	5.16

wetland restoration controls flooding, reducing the risks of the DL water overspill. Further, we found that climate change is increasing the risks of flooding in DL watershed, similar to the general trends in the Nelson River basin (Hirabayashi et al., 2013) and indicating a general increase of flood risks in future climates (Arnell and Gosling, 2016). These results make a strong case for wetland protection and restoration as a viable flood management option.

Wetland protection however carries significant costs and had variable success. According to North Dakota State Water Commission, a simple earth plug closing a wetland drain costs $450. Given an estimated loss of 23,000 wetlands with the total area of 166 km^2, compensation to landowners and other expenses, the restoration costs were estimated at $31.4 million with a benefit-to-cost ratio at 0.2 to 1 (Gehringer and Hove, 1998). Another study of flood risk reduction through wetlands restoration in the Maple River Watershed, which is also a part of the North Dakota Prairie Pothole region, estimated similar benefit-to-cost ratios between 0.2 and 0.7 (Shultz and Leitch, 2003). The assumed low benefit-to-cost ratio detract appropriation of public funds for wetland restoration (Shultz and Leitch, 2003). In the Devils Lake watershed, the 1996–1999 Available Storage Acreage Program (ASAP) restored 52 km^2 of wetlands storing 0.23 km^3 of water under one-year contracts with landowners (U.S. Army Corps of Engineers, 2003). The revised 10-year Extended Storage Acreage Program ESAP (North Dakota State Water Commission, n.d.) was underfunded and had minimal success.

The reports on ineffectiveness of the wetland restoration based on the benefit-cost analysis probably did not account for the flood damage and mitigation costs, which exceeded $1B for the case of Devils Lake flooding. Zheng et al (2014) studied flood mitigation strategies and concluded that the seemingly counterintuitive selection of the high-cost flood mitigation options is explained with discounting of the future risks by policymakers and the preferential treatment of near-term remedies instead of long-term solutions. We suggest that a similar discounting of the long-term risks took place in wetland restoration decision, which carries high initial costs but long-term benefits in terms of reduced flooding area as seen from Table 3. Meanwhile, model simulations using early intervention scenarios with increased wetland demonstrate significant reduction in flooded area and in water outlet needs under the current climate (Table 2).

In a seemingly absence of an economically viable alternative, controlled water release from the lake was selected as the main option of flood management. It is estimated that the outlets have reduced the lake

level by 0.7 m (Shabani et al., 2017). The downside of this decision is downstream water quality impairment, accelerated downstream flooding, and risks of introduction of non-native species and fish parasites to Lake Winnipeg (Ma et al., 2011). Indeed, DL water at the East Bay outlet contains 5000 mg/L of dissolved solids and 500 mg/L of dissolved sulfates (Sether et al., 1998; Shabani et al., 2017; Wiche, 1998). Pumping this water elevates Sheyenne River sulfates concentration (Shabani et al., 2017), exceeding the state limits for Class IA streams. The concerns about environmental impacts of DL water management lead to multiple protests in communities of the Red River of the North valley, including those from the Manitoba Government (Kharel et al., 2018). Currently, the downstream water quality and the risks of biota transfer across the international border are controlled through regular water quality monitoring as part of the agreement made in 2005 between the U.S. and Canada (North Dakota State Water Commission, 2017). The currently implemented outlet based solution is a delicate mitigation strategy prone to uncertainties related to climate change, biota-transfer, downstream water quality and inter-basin water transfer (Flanders, 2006; Ma et al., 2011).

Future climate exacerbate flooding problem, creating a higher need for water control in DL. A viable alternative would be expansion of the efforts in wetland restoration. Even though the importance of wetland protection and restoration will increase in future climates, the pressures on existing wetlands will also increase. At the same time, climate change will make the wetland restoration and management more complex through alternations in the hydrological regime, mainly through changes in temperature and precipitation patterns, and through impacts on the wildlife habitat. As a result, in absence of intervention the number of functioning wetlands is projected to decline and the geographic location of the wetland types will shift. A model based study in the Northern Great Plains pothole region indicated risks of decreased water levels and increased vegetation cover (Johnson et al., 2005). That will make the wetland restoration projects dependent on a larger context of climate change mitigation and adaptation efforts (Erwin, 2009).

Despite the recognized role of the regional climate change in controlling DL water level, flood management does not account for the climate change related risks. A recent study of the local stakeholders involved in the flood management of the DL and downstream watersheds found very limited discussion of climate change and a lack of concrete plans to incorporate climate change into the long-term flood mitigation strategy (Kharel, 2015; Kharel et al., 2018), weakening the resilience of local communities. Devils Lake flooding is a multi-jurisdictional and multi-faceted “wicked” environmental problem (Gruszczynski and Michaels, 2014; Kharel et al., 2018). By nature, wicked problems do not have a optimal solution (Balint et al., 2011), therefore these types of problems require outside-the-box solution approach that ensures multi-stakeholder collaboration, multidisciplinary understanding, and consideration of uncertainties (Conklin, 2005; Lazarus, 2008; Palmer et al., 2007; Van Bueren et al., 2003; Weber and Khademian, 2008). Kharel et al. (2018) proposed a unique solution approach – ‘green paradiplomacy’– for the transboundary Devils Lake flooding problem in the Red River Basin along the US-Canada border.

5. Conclusion

Globally, the area of wetlands is shrinking with multiple impacts on water quality and ecosystems. One of the important roles of wetlands is reduction of flood risks. In this regard, closed hydrologic systems provide the benefit of simplicity in estimation of wetland loss impact on flood risks. We developed a model of Devils Lake (North Dakota, USA) and estimated impacts of wetland loss and restoration as mitigation alternatives to the ongoing large scale flooding disaster. We found wetland loss a significant contributor to flooding, in addition to the regional climate change. We also noted increasing flood risks in the next three decades under regionally downscaled CMIP-5 climate parameters. Under the modified climate, wetland restoration alone does not prevent acceleration of flood risks. However, wetland restoration presents a good complementary measure reducing the negative impacts of other flood management strategies.

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Appendix. SWAT model setup, calibration, and validation.

Model setup

The hydrology of the Devils Lake basin was simulated with the Soil and Water Assessment Tool (SWAT 2012) (Neitsch et al., 2011). The data that were used to develop the hydrological model of devils Lake watershed for this study included: digital elevation model (DEM), river network, land cover types, soil and slope classes, observed historical climate, and lake and wetland information. We used a 30 m DEM from the National Elevation Dataset (U.S. Geological Survey, 2009) because previous studies indicated that higher DEM resolution has no significant improvement of streamflow and runoff simulation (Lin et al., 2013; Tan et al., 2015). For river network, the National Hydrography Dataset (U.S. Geological Survey, 2013) was used. The land cover map was extracted from the National Land Cover Dataset (Fry et al., 2011; Homer et al., 2007). To reduce computational requirements, the original NLCD land cover types were aggregated into 7 types by joining similar classes. Soil data was obtained from the STATSGO database (U.S. Department of Agriculture, 1993).

First, the DEM and river network were used to delineate the watershed, divide it into 96 sub-basins and generate the associated topographic characteristics including stream geometry and slope classes for each sub-basin. Second, land cover, soil and slope maps were overlaid. Third, a threshold of 5% land cover, 20% soil, and 15% slope was defined in each sub-basin to generate 452 hydrologic response units (HRUs). Devils Lake was represented as a reservoir with its associated functional properties (Table A1).

Table A1
Devils Lake reservoir volume and surface area used in the model.

Parameter, unit	Description	Values
RES_VOL, 10^4 m^3	Initial volume of water in reservoir on the first day of simulation	85,000
RES_PVOL, 10^4 m^3	Volume of reservoir when filled to principal spillway	333,650
RES_PSA, ha	Surface area of reservoir when filled to principal spillway	56,092
RES_EVOL, 10^4 m^3	Volume of reservoir when filled to emergency spillway	536,600
RES_ESA, ha	Surface area of reservoir when filled to emergency spillway	97,800

(U.S. Geological Survey, 2011).

Table A2
Wetland volume and area used for different wetland scenarios in the model.

Parameter, unit	Description	Wetland scenarios				
		0% wetlands	5% wetlands	11% wetlands (current)	16% wetlands	20% wetlands
WET_MXVOL, 10^4 m^3	Volume of water stored in wetlands when filled to maximum water level	–	19,362	58,463	111,252	141,554
WET_MXSA, ha	Surface area of wetlands at maximum water level	–	47,575	102,202	152,256.4	190,299
WET_FR	the fraction of subbasin area that drains into wetlands	–	0.05	0.11	0.17	0.22

Table A3
SWAT model parameters with the default and fitted values used for model parametrization.

Parameter	Description	Default Value	Fitted Value
SFTMP.bsn*	Snowfall temperature (°C)	1	0.58
SMTMP.bsn*	Snow melt base temperature (°C)	0.5	1.28
SMFMX.bsn*	Melt factor for snow on June 21 (mm H_2O/°C-day)	4.5	5.5
SMFMN.bsn*	Melt factor for snow on December 21 (mm H_2O/°C-day)	4.5	2.25
TIMP.bsn*	Snow pack temperature lag factor	1	0.33
SNOCOVMX.bsn*	Minimum snow water content that corresponds to 100% snow cover, SNO_{100} (mm H_2O)	1	14
EVLAI.bsn*	Leaf area index at which no evaporation occurs from water surface	3	3.8
GW_DELAY.gw	Groundwater delay time (days)	31	331.79
ALPHA_BF.gw	Baseflow alpha factor (1/days)	0.048	0.74
GWQMN.gw	Threshold depth of water in shallow aquifer required for return flow to occur (mm H_2O)	1000	4400.16
GW_REVAP.gw	Groundwater "revap" coefficient	0.02	0.04
REVAPMN.gw	Threshold depth of water in the shallow aquifer for "revap" or percolation to the deep aquifer to occur (mm H_2O)	750	48.95
RCHRG_DP.gw	Deep aquifer percolation fraction	0.05	0.88
OV_N.hru	Manning's "n" value for overland flow	−999	−0.08**
ESCO.hru	Soil evaporation compensation factor	0.95	0.30
EPCO.hru	Plant uptake compensation factor	1	0.77
CN2.mgt	Initial SCS runoff number for moisture condition II	−999	0.02**
CH_N(2).rte	Manning's "n" value for the main channel	0.014	0.12
ALPHA_BNK.rte	Baseflow alpha factor for bank storage (days)	0	0.40
CH_N(1).sub	Manning's "n" value for the tributary channels	0.014	8.72
EVRSV.res	Lake evaporation coefficient	0.6	0.85

**Parameters with relative change fitted value: $P = DP * (1 + RCP)$, where DP is a default parameter value and RCP is a calibrated Relative Change Parameter value.
*Parameter values were adapted from Kharel and Kirilenko (2015).

Table A4
Model performance at the USGS streamflow gauging stations within the watershed.

USGS Gauges	Nash-Sutcliffe Model Efficiency (NSE)	
	Calibration	Validation
Mauvais coulee*	0.55	0.63
Edmore coulee*	0.71	0.74
Edmore coulee tributary*	0.74	0.69
Starkweather coulee*	0.51	0.67
Little coulee**	0.73	0.56
Big coulee***	0.61	0.66
Channel A***	0.86	0.7

Note. As constrained by the observation data availability, the model was calibrated and validated for varying time periods. The USGS gauges with * calibration (2001–2010) and validation (1991–1998); ** calibration (2005–2010) and validation (1998–2004); ***calibration (1996–1998) and validation (1991–1995).

Table A5
Simulated Devils Lake water levels compared with the observations.

Period	Mean observed elevation, m	Mean simulated elevation, m	%Bias	r	NSE	RMSE, m	RSR	SD, m
1991–2000	437.33	437.81	−11.0	0.99	0.95	0.59	0.22	2.7
2001–2010	441.33	441.27	1.4	0.96	0.9	0.14	0.31	0.44
1991–2010	439.33	439.54	−4.8	0.99	0.98	0.43	0.15	2.78

The wetlands in the watershed were modeled as a fraction of sub-basin area using the 'wetland' utility available in SWAT which requires three important input parameters (Table A2). We estimated the required wetlands parameters using a statistical model developed for the Prairie Pothole Region (Gleasonet al., 2008):

$$V = 0.25A^{1.4742} \quad (1)$$

$$UA = 2.24A^{0.4647} \quad (2)$$

where *V* represents predicted wetland volume, *A* wetland area, and *UA* upland zone area.

Model calibration and validation

The SWAT model was calibrated and validated for the daily observations of the seven USGS streamflow gauges within the watershed and Devils Lake water levels for the 1989 – 2010 period (Table A4) with assistance of automated calibrator, SWAT-CUP (Abbaspour, 2007). The model was calibrated for 21 parameters related to snow, water balance, evapotranspiration (Table A3). The streamflow calibration and validation indicated a satisfactory model performance with the Nash-Sutcliffe model efficiency (NSE) values ranging from 0.51 to 0.86 between different gauges (Moriasi et al., 2007) (Table A4). For the reservoir simulation, the model was calibrated for ten years (2001 – 2010) with 1999–2000 warm up and validated for ten years (1991 – 2000) with 1989–1990 warm up. Since the Devils Lake outlets were rarely used and not fully functional prior to 2011, the pumped out water from the lake was negligible, and therefore, the effect of outlets during the model calibration-validation period can be safely ignored. In future climate simulations, we assumed that the outlets pump 11.2 m^3/s during the months when the lake is typically not frozen (March – November). These values were estimated based on the reported 2011 – 2014 outlet operation schedule.

Model calibration against the observed elevation of Devils Lake was carried out using the RMSE to standard deviation ratio (RSR) (equation 3) as the objective function (Abbaspour, 2007; Moriasi et al., 2007). Devils Lake level was calibrated with RSR = 0.31 and validated with RSR = 0.22 (Figure 3, Table A4). Additionally, Pbias values for the calibration and validation results were found 1.4% and 11% respectively. The values of RSR below 0.5 and Pbias within ± 25% are considered a very good performance (Moriasi et al., 2007) Table A5.

$$RSR = \frac{RMSE}{STDEVobs} = \frac{\sqrt{\Sigma_{i=1}^{n}(Y_i^{obs} - Y_i^{sim})^2}}{\sqrt{\Sigma_{i=1}^{n}(Y_i^{obs} - Y^{mean})^2}}$$

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